

REPORT DOCUMENTATION PAGE

Form Approved

OMB NO. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimates or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarter Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY(Leave blank)

2. REPORT DATE

August 2, 1999

3. REPORT TYPE AND DATES COVERED

Final, August 1, 96 - July 31, 99

4. TITLE AND SUBTITLE

FREE-SPACE ELECTRO-OPTIC SAMPLING AND 2D THZ IMAGING

5. FUNDING NUMBER

DAAH04-96-1-0370

6. AUTHOR(S)

X.-C. Zhang

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Rensselaer Polytechnic Institute
Physics Department
110 8th Street
Troy NY 12180 USA

8. PERFORMING
ORGANIZATION
REPORT NUMBER

19991102 107

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING
AGENCY REPORT NUMBER

ARO 35167.1-PH

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release: distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT(Maximum 200 words)

Ultrafast electro-optic sampling technique, which is primarily used for local electric field characterization in integrated circuits, has been applied to free-space applications. Electro-optic sampling for characterizing freely propagating terahertz beams has been demonstrated with femtosecond temporal resolution and sub- μ V sensitivity. We also achieved real-time 2D THz imaging with parallel optical reconstruction with a CCD camera. We also developed an electro-optic THz streak camera.

14. SUBJECT TERMS

15. NUMBER IF PAGES

7

16. PRICE CODE

17. SECURITY CLASSIFICATION
OR REPORT
UNCLASSIFIED18. SECURITY CLASSIFICATION
OF THIS PAGE
UNCLASSIFIED19. SECURITY CLASSIFICATION
OF ABSTRACT
UNCLASSIFIED20. LIMITATION OF ABSTRACT
UL

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

Problem Studied:

Ultrafast electro-optic sampling technique, which is primarily used for local electric field characterization in integrated circuits, has been applied to free-space applications. Electro-optic sampling for characterizing freely propagating terahertz beams has been demonstrated with femtosecond temporal resolution and sub- μV sensitivity. We also achieved real-time 2D THz imaging with parallel optical reconstruction with a CCD camera. We also developed an electro-optic THz streak camera.

Summary of the most important results:

Electro-optic sensor for THz beams makes it possible for us to see images of electric fields, diseased tissue, the chemical composition of plants, and much more that is undetected by other imaging systems. We have designed and tested several electro-optic THz sensors for characterization of the temporal and spatial distribution of free-space broadband, pulsed electromagnetic radiation (THz beams). This THz optoelectronic detection system, which uses electro-optic crystals, provides diffraction-limited spatial resolution, fs temporal resolution, DC-THz spectral bandwidth, and mV/cm field detectability. The sensitivity and bandwidth of the electro-optic detectors are comparable or superior to the best ultrafast photoconductive dipole antennas, liquid helium cooled bolometers, or any other terahertz detectors currently available.

Advantages intrinsic to electro-optic detection include nonresonant frequency response, large detector area, high scan rate, low optical probe power, and large linear dynamic range. The concept of a free-space electro-optic detection system, similar to local field electro-optic sampling, is based on the Pockels effect in electro-optic crystals where a pulsed microwave signal (DC-THz) acts as a transient bias to induce a transient birefringence which can be detected by a synchronous optical probe. THz field measurements using ZnTe as an electro-optic crystal in a collinear geometry have demonstrated a signal-to-noise ratio (SNR) exceeding 1,000,000.

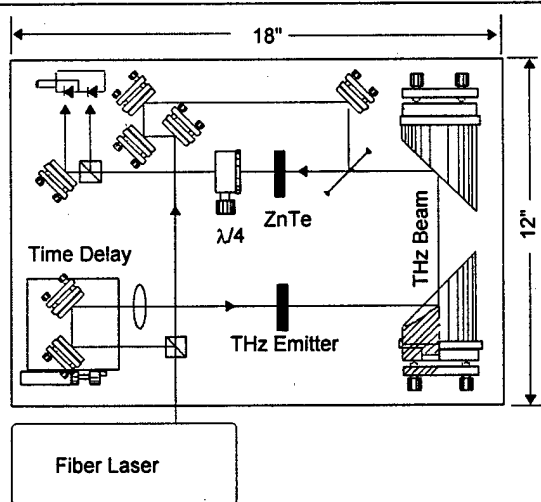


Fig. 1. Schematic for a portable electro-optic system for the generation and detection of free-space THz beam.

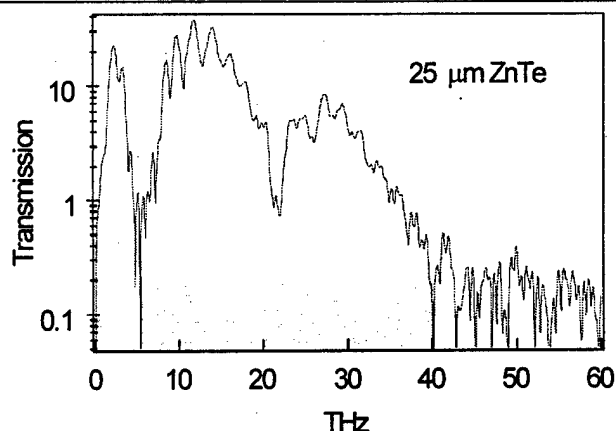


Fig. 2. Frequency spectrum of THz field in Fig. 8. The absorption dips at 5.3 THz is due to the phonon band.

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

Electro-optic generation and detection provide new method for the measurement of freely propagating pulsed electromagnetic radiation. Figure 1 shows a portable THz system. The recent experimental results of electro-optic detection of THz beams demonstrate an oscillation period of a mid-infrared THz beam as short as 27 fs. The upper-limit of frequency reaches to 37 THz (8 μm), as shown in Figure 2.

In theory, many biological and organic compounds have distinct signatures within the terahertz region, meaning that their chemical compositions might be examined by the Rensselaer system. Such a capability could be applied to the diagnosis of disease, detection of pollutants, or quality control of food products. It is also quite possible that plastic explosives look very different under terahertz light and could be distinguished from the molecular structure of suitcases, clothing, and common household materials and equipment. THz imaging is extremely sensitive to the water concentration in the samples.

Until now, no technology existed that could use this radiation to rapidly create images. The electro-optic sensor can create real-time images with 250,000 pixels, it is also capable for single-shot imaging. Using an optically chirped pulse in an electro-optic detection system, we demonstrate single-shot THz field imaging of the spatial and temporal distribution of a THz pulse from photoconductive emitters. Unparalleled by other THz sampling techniques, this single-shot method provides what is believed to be the highest possible data-acquisition rate.

Figure 3 shows the THz images from a mammographic phantom which is designed to test the performance of a mammographic system by a quantitative evaluation of the system's ability to image small structures similar to those found clinically. The THz system shows an excellent spatial resolution. Images of these fibers, masses and specks with their thickness as small as 0.24 mm have been resolved.

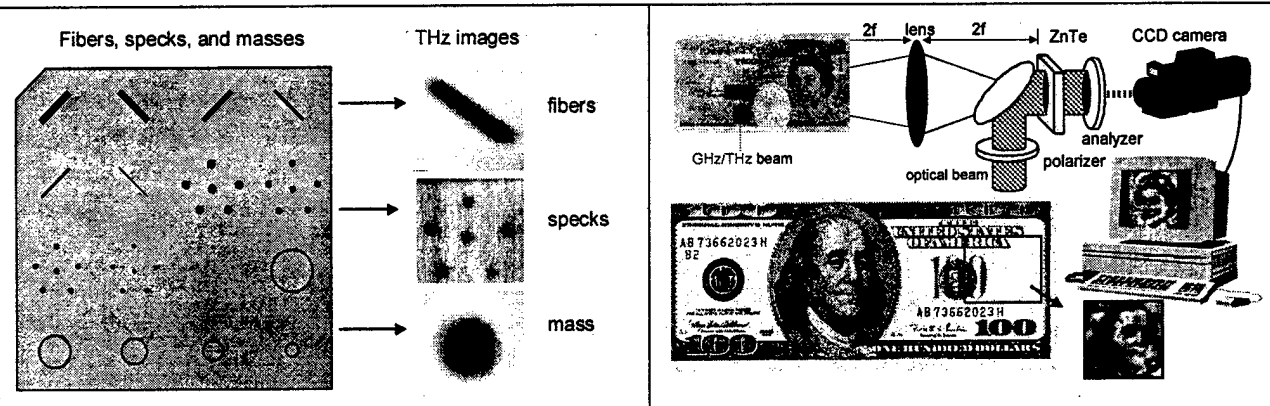


Fig. 3. THz images of fiber, mass and speck. Small structures with a thickness less than 0.5 mm and a diameter less than 0.24 mm can be resolved.

Fig. 4. THz image based on the phase difference of currency watermark structure. A phase shift as small as a few femtosecond can be resolved.

Figure 4 shows the schematic for THz imaging of the currency watermarks. Unlike intensity images viewed with a visible beam, the watermark images are obtained purely by the phase difference of the THz pulse transmitted through the watermarks. The maximum phase shift is less than 60 fs and this value is within our system resolution. The THz absorption is shown to be less

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

than 0.5%. Clearly these THz watermark images in the THz spectrum show an alternative method for anti-counterfeiting.

Unparalleled by technique using photoconductive antennas, for the free-space electro-optic sampling a time-wavelength de-/multiplexing is possible. Using linearly chirped optical probe pulse the temporal THz waveform can be encoded onto the frequency spectrum [1]. The encoded temporal information is, then, retrieved in the wavelength domain. Real-time and single-shot acquisition of picosecond THz field pulses is achieved without using a mechanical time-delay line. Figure 5 schematically illustrates the concepts of electro-optic measurement with the standard sampling method incorporating a chirped optical probe beam. A grating pair is used for chirping the optical pulse in the frequency domain and stretching the pulse in the time domain. The time-dependent spectral distribution of the optical pulse has blue components leading the red components.

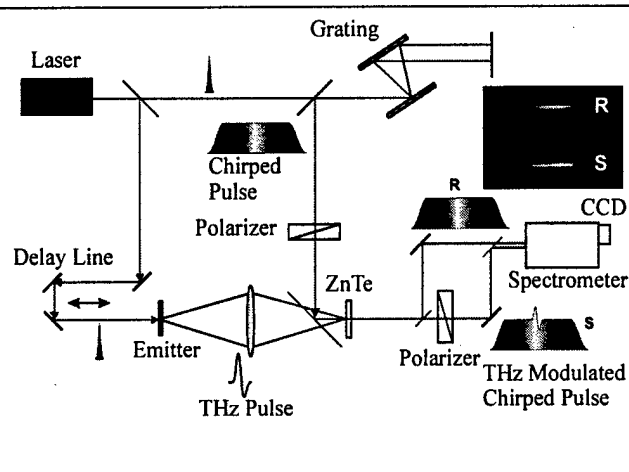


Fig. 5. Schematic of experimental setup of electro-optic measurement with a chirped optical probe beam. Images of the chirped probe pulses. S and R denote for image traces of signal and reference beam, respectively.

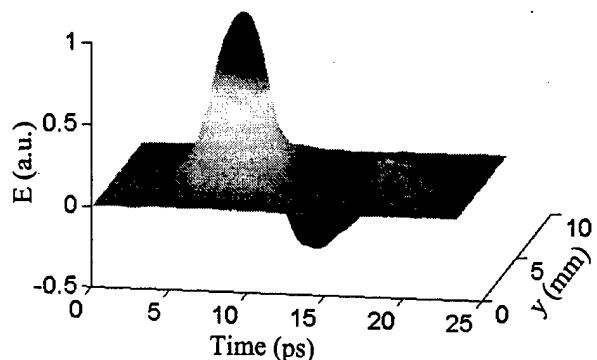


Fig. 6. A single-shot spatio-temporal (10 mm - 25 ps) image of a THz pulse measured by chirped optical probe pulse. The emitter is a dipole antenna with a gap of 7 mm.

The temporal THz signal is extracted by measuring the difference between the spectral distributions of the probe pulse with and without THz pulse modulation. Two insets in Figure 5 are the spectral distributions of the chirped probe pulse measured by a CCD camera with and without THz signal. The normalized distribution reconstructs both the amplitude and phase of the temporal waveform of the THz pulse.

The electro-optic measurement with chirped optical probe pulse is capable of single-shot measurement of a full THz waveform [2]. Figure 6 is a plot of the *single-shot* image from a GaAs photoconductive dipole antenna with a bias voltage of 5 kV. The THz waveform as well as the symmetric spatial distribution of the far-field pattern from the dipole antenna is well observed. The total time for wavelength division multiplexing and demultiplexing is within a few picoseconds. One-dimensional spatial field distribution of the THz beam across the dipole and its temporal waveform are obtained simultaneously with a single laser pulse. The size of the spatio-temporal image is 10 mm by 25 ps. To our knowledge, this is the first demonstration of a single-shot image of THz pulse.

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

Reference:

- [1] Zhiping Jiang and X.-C. Zhang, *Appl. Phys. Lett.* **72**, 1945 (1998).
- [2] Zhiping Jiang and X.-C. Zhang, *Opt. Lett.* **23**, 1114 (1998).

Tangible Outcomes:

Report of free-space electro-optic sampling and THz imaging. *Appl. Phys. Lett.* 67, 3523, (1995); 68, 1604 (1996); 68, 2924, (1996); 68, 3224, (1996), *Appl. Phys. Lett.* 69, 1026 (1996); 70, 1784 (1997); 71, 1285 (1997); 71, 1452 (1997), 72, 1945 (1998), 73, 3049, (1998), March 1 issue (1999); *Optic Letters*, 23, 1114 (1998); and *J. Opt. Soc. Am.* B15, 1795 (1998).

Rensselaer's recent work on terahertz technology was featured in *Photonic Spectrum* (Feb. issue, 1999), *Laser Focus World* (Mar. issue, 1998; Oct. issue 1997; Feb. issue 1997), *Optics & Photonics News* (Dec. issue 1996), and *Business Week* (May 5 issue, 1997). An extensive publicity campaign also led to coverage by *New Scientist*, ABC News Radio, *Reuter*, *Time*, *Centre Daily Time*, *R&D Research and Development*, *Reference News*, *Laser and Optronics*, *Daily Telegraph*, *Industry Week*, *R&D Magazine*, *Aviation Week & Space Technology*, *Design News*, *Ledger-Enquirer*, *Law Enforcement Technology*, *Knight-Ridder*, *Science Spectrum*, and *Physics Today*.

During the last several years, scientists from NASA Goddard Space Flight Center, GE CR&D, Intel, Lucent Technologies, Naval Research Lab., Army Research Lab., Phillips Air Force Lab. Rome Lab., NIST, and over 30 universities, companies, clinics, and medical schools have visited our laboratory and have used our electro-optic sensors. We have also helped scientists and researchers from Australia, Canada, Denmark, Holland, United Kingdom, Japan, Korea, Brazil, Czech Republic, France, Germany, People's Republic of China, and Taiwan learn the use of our electro-optic sensors. Some potential commercial applications of our research are in the fields of THz spectroscopy, electric field sensors, and medical imaging.

Refereed Journal Publications and Conference Proceedings after 1996:

- 1. X.-C. Zhang, Q. Wu, and T. D. Hewitt, "Electro-Optic Imaging of Terahertz Beams," *Ultrafast Phenomena X*, Springer Series in Chemical Physics, 54 (1996).
- 2. Q. Wu, M. Litz, and X.-C. Zhang, "Free-Space Electro-Optic Samplers," *Ultrafast Phenomena X*, Springer Series in Chemical Physics, 60 (1996).
- 3. X.-C. Zhang, "Generation and Detection of Terahertz Electromagnetic Pulses from Semiconductors with Femtosecond Optics," *J. Luminescence*, 66&67, 488 (1996).
- 4. X.-C. Zhang, "Free-Space THz Optoelectronics," Tara McGraw Hill, Raina and Vaya, *Photonics*, 1, 443 (1996).
- 5. Q. Wu and X.-C. Zhang, "Electro-Optic Sampling of Freely Propagating THz Fields," *Optics & Quantum Electronics*, 28, 945 (1996).
- 6. Q. Wu and X.-C. Zhang, "Ultrafast Electro-Optic Field Sensors," *Appl. Phys. Lett.*, 68, 1604 (1996).
- 7. Q. Wu, M. Litz, and X.-C. Zhang, "Broadband Detection Capability of Electro-Optic Field Probes," *Appl. Phys. Lett.*, 68, 2924 (1996).
- 8. Q. Wu, F.G. Sun, P. Campbell, and X.-C. Zhang, "Dynamic Range of an Electro-Optic Field

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

- Sensor and Its Imaging Applications," *Appl. Phys. Lett.*, 68, 3224 (1996).
9. Q. Wu, T.D. Hewitt, and X.-C. Zhang, "Electro-Optic Imaging of Terahertz Beams," *Appl. Phys. Lett.*, 69, 1026 (1996).
 10. X.-C. Zhang and Q. Wu, "New Terahertz Beams Imaging Device," *Optics & Photonics News*, 12, 9 (1996).
 11. X.-C. Zhang, Q. Wu, P. Campbell, and L. Libelo, "New Field Sensors for Subpicosecond Electromagnetic Pulses," *Ultrafast Processes of Spectroscopy*, 649, Plenum Press, New York, (1996).
 12. X.-C. Zhang, B.H. Kolner, and K. Leo, "Introduction to the Issue on Ultrafast Electronics, and Optoelectronics," *IEEE-JSTQE*, 3, 433 (1996).
 13. Q. Wu and X.-C. Zhang, "Design and Characterization of Traveling-Wave Electro-Optic THz Sensors," *IEEE-JSTQE*, 3, 693 (1996).
 14. Z.G. Lu, P. Campbell, and X.-C. Zhang, "Free-Space Electro-Optic Sampling with a High-Repetition-Rate Regenerative Amplified Laser," *Appl. Phys. Lett.*, 71, 593 (1997).
 15. Q. Wu and X.-C. Zhang, "7 THz Ultrabroadband GaP Electro-Optic Sensors," *Appl. Phys. Lett.*, 70, 1784 (1997).
 16. Q. Wu and X.-C. Zhang, "Free-Space Electro-Optic Sampling of Mid-Infrared Pulses," *Appl. Phys. Lett.*, 71, 1285 (1997).
 17. J. Riordan, F.G. Sun, Z.G. Lu, and X.-C. Zhang, "Free-Space Magneto-Optic Sampling," *Appl. Phys. Lett.*, 71, 1452 (1997).
 18. Zhiping Jiang and X.-C. Zhang, "Electro-optic Measurement of THz Pulses with a Chirped Optical Beam," *Appl. Phys. Lett.*, 72, 1945 (1998).
 19. H.J. Bakker, G.C. Cho, H. Kurz, Q. Wu, and X.-C. Zhang, "Distortion of THz Pulses in Electro-Optic Sampling," *J. Opt. Soc. Am. B* 15, 1795 (1998).
 20. P. Campbell, M. Li, Z.G. Lu, J.A. Riordan, K. R. Stewart, G.A. Wagoner, Q. Wu, and X.-C. Zhang, "Free-Space Electro-Optic and Magneto-Optic Sampling," *SPIE proceeding*, 3269, 114 (1998).
 21. P.Y. Han, J.A. Riordan, Z.P. Jiang, and X.-C. Zhang, "Electro-Optic and Magneto-Optic sensors for THz beams," *SPIE proceeding*, 3277, 198 (1997).
 22. Zhiping Jiang and X.-C. Zhang, "Single-Shot Measurement of a THz Pulse," *Engineering Laboratory Note, Optic & Photonic News*, 9, No.8, 37, (1998).
 23. J.A. Riordan, P.Y. Han, Z.P. Jiang, P. Campbell, Z.G. Lu, and X.-C. Zhang, "THz Beam Sensors," *Radiative Processes and Dephasing in Semiconductors, Trends in Optics and Photonics*, Vol. XVIII, 108, (1998).
 24. Zhiping Jiang and X.-C. Zhang, "Single-Shot Spatial-Temporal THz Field Imaging," *Optic Letters*, 23, 1114 (1998).
 25. F.G. Sun, Zhiping Jiang and X.-C. Zhang, "Analysis of THz Pulse Measurement with a Chirped Probe Beam," *Appl. Phys. Lett.*, 73, 2233, (1998).
 26. P.Y. Han and X.-C. Zhang, "Coherent, Broadband Mid-Infrared Terahertz Beam Sensors," *Appl. Phys. Lett.*, 73, 3049, (1998).
 27. X.-C. Zhang and Zhiping Jiang, "Imaging of Far-Infrared THz Pulses," *Hot Topics, LEOS Newsletter*, 12, 7 (1998).
 28. Q. Chen and X.-C. Zhang, "Polarization Modulation in Optoelectronic Generation and Detection of Terahertz Pulses," submitted to *Appl. Phys. Lett.*, (1999).
 29. Zhiping Jiang, F. G. Sun, Q. Chen, and X.-C. Zhang, "Electro-Optic Sampling near Zero

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

- Optical Transmission Point," *Appl. Phys. Lett.*, March 1 issue, (1999).
30. M. Li, G. C. Cho, T.-M. Lu, X.-C. Zhang, S.-Q. Wang and J.T. Kennedy, "Time-Domain Dielectric Constant Measurement of Thin film in GHz-THz Frequency Range near the Brewster Angle," *Appl. Phys. Lett.*, April 12 issue, (1999).
31. P.Y. Han, G.C. Cho, and X.-C. Zhang, "Broad Band Mid-Infrared THz Pulse: Measurement Technique and Applications", to be published in *Journal of Nonlinear Optical Physics and Materials*, (1999).

Student Research Supervision:

During the last three years, PI has graduated 4 Ph.D. students and 6 M.Sc. students, and PI also advises 3 postdoctoral research associates and 9 Ph.D. students. Four senior research scientists from Japan, Australia, and Singapore work with us from 6 months to 2 years. A graduate student, Ms. Jennifer Riordan, supported by ARO, defended her thesis on March 8, 1999, and she is working at Corning now.